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ON AURORAL ELECTRONS

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by

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Abstract:

The results of rocket studies of the energy spectra of primary auroral electrons are reviewed. Many of these spectra display peaks and discontinuities in the range 3 keV to 12 keV which indicate, very unambiguously, that these electrons were energized by an electric field. Moreover the observations directly demonstrate that these electrons were trapped on closed field lines restricting the electric field to one that is normal to the magnetic field.

Further observations, primarily of electrons of greater than 10 keV, show that a second impulsive acceleration process supplements the basic electrostatic mechanism. A beam-plasma instability is suggested as being the cause of this acceleration and certain features of such a process are outlined. Direct evidence is presented that the dynamic acceleration occurs very close to the atmosphere (1000 km altitude).

A working model of the development of an auroral display through the quiet phase to the breakup is advanced based upon these two acceleration mechanisms.

Introduction

The study of the charged particle influx which produces the visual aurora is largely directed toward answering the questions "how were these auroral particles energized?" and "how and why are they precipitated into the atmosphere so as to produce the morphology observed in the visual aurora?"

In this effort much emphasis has been placed upon the measurement of the energy spectra of the auroral particles in the hope that certain spectral characteristics may emerge, for example peaks in the spectrum, which could be linked to specific acceleration mechanisms. Nonetheless important is the study of the temporal behavior of the precipitating particles. Greater knowledge of periodic variations in the particle flux (pulsating aurora suggests such behavior exists) should have bearing on some of the more dynamic mechanisms influencing auroral particles. Much interest has recently been shown in the careful observations of transient or rapid time changes in auroral electron intensities in the hope that measurements of electron velocity dispersion may result in fixing the position in the magnetosphere where these intensity fluctuations are originating.

Studies along these lines are beginning to produce results (Evans 1966, 1967 a,b; Mozer and Bruston 1966; Lampton et al, 1967, Albert, 1967).

This paper describes some of these results in detail and attempts to link the various observations together into a natural sequence in time which would correspond to the development of an auroral display,

The Static Phase

Studies of the visual aurora suggest there is a phase of the display which may loosely be termed the quiet or static phase. Such auroras are generally observed in the evening and pre-midnight hours and can be characterized by arcs or bands extending in an east-west direction for some distance while being typically 5 - 10 km thick in the north-south direction. These bands usually do not exhibit rapid motion, on occasion being virtually stationary for tens of minutes. Moreover the overall luminosity of such forms remains quite constant over similar periods of time. The net subjective impression of these auroras justifies the term quiet arc.

Observations of electron energy spectra (generally in the energy range above 20 - 30 keV) made with detectors in rockets fired through auroral displays have usually shown extremely variable intensities and energy spectra, characteristics which seem in qualitative disagreement with what would have been expected from the appearance of the quiet phase of the auroral display. While this result may occur, to an extent, because most observations are made during the more dynamic breakup phase of the display, some evidence of the earlier static nature of the aurora could still be present in the particle influx. Recently observations have exposed a static characteristic in the auroral electron influx, a feature which appears so far to be confined to energies below 15 keV.

Evans (1966) reported the observation, made on two separate rocket flights into breakup aurora, of a distinctive feature in the electron energy spectrum which was very stable over periods of 200 seconds.

In the first case (Figure 1) a sharp break or knee in the electron energy spectrum was observed at an energy of about 11 keV. This knee continued to be observed for more than 200 seconds of flight time. The second example was that shown in Figure 2 of a very prominent peak in the electron energy spectrum at approximately 6 keV. The stability in the position of this spectral feature over a period when the flux of 40 keV electrons was undergoing orders of magnitude changes was specifically pointed out.

Albert (196%) reported the observation, using a rocket borne, high energy resolution electron spectrometer, of a nearly monoenergetic beam of electrons associated with an auroral display. Again the relative stability of the characteristic energy (near 10 keV) was a notable feature of the data.

Evans (1967b) reports a further observation of such a nearly manoenergetic beam of electrons, this instance of note because the aurora that the rocket was launched into was of the prebreakup type (the disturbance component of the geomagnetic field was $< 20\gamma$). Figure 3 displays a very typical response curve produced by the electrostatic-analyzer-channel-multiplier detector system as it was swept through the energy range 1.5 keV - 10 keV during this rocket flight. The solid line is the response curve that would have been observed had the auroral electron beam been composed entirely of 3.8 keV electrons. The close agreement between the observed and the hypothetical curves in Figure 3, particularly over the higher energy portion of the spectral peak, lead to the conclusion that if that portion of the actual electron energy spectrum were fitted to an exponential form e^{-E/E_o}, E_o would be less than 100 eV.

As in previous observations of this sort of spectrum, the stability of the peak was a most striking feature of these measurements. Figure 4, where the energy of this spectral peak is plotted against flight time, illustrates this stability during a 150 second period.

It is seen that the spectra described above have two outstanding characteristics, first the existence of prominent spectral features and secondly the stability of the energy associated with this feature as a function of time.

The appearance of a spectral peak or discontinuity seems to be most satisfactorily explained by models in which the electrons have acquired their energy by moving or being driven through an electrical potential difference. This is especially true for the spectrum shown in Figure 3, where the high energy tail-off is so extremely steep.

The geometry of this potential distribution is not clear as yet. One choice would be a 3.8 keV potential difference imposed along a magnetic line of force. However the stable nature of this potential, as evidenced by the stability in the observed electron energy spectra, would seem to speak against such a voltage distribution as it has been argued that the resultant electric fields cannot be sustained in the presence of plasma. Moreover it has been pointed out (for example Mende, 1967) that it would be impossible to prevent the ionosphere from evaporating if such an electric field were present at low altitude - i.e., the existence of the auroral ionosphere precludes the existence of a longitudinal electric field at those altitudes, On the other hand the observations reported by Evans could not be interpreted as excluding the electrons being energized by an electric field aligned along the magnetic field.

Because of the controversy surrounding longitudinal electric fields, alternative electric field geometries should be considered, the most attractive of which is a transverse electric field. As Evans stresses, the acceleration of the electron in this sort of potential distribution depends in general upon drift trajectories determined by magnetic gradient and line curvature drifts - not directly by the electric field. This, however, appears to lead to the requirement that the electrons undergoing acceleration be trapped upon closed field lines, for to place the particle on an open field line and demand that magnetically controlled drifts be sufficient to drive the particle across as much as 13 kV potential difference in a single traversal down the magnetic field line would require either

(a) a very unusual field geometry resulting in longitudinal electron drifts on the order of 100's of km per traversal, or

(b) an unreasonably large transverse electric field intensity.

The resultant picture of the production of auroral electrons which have this "potential difference signature" in their energy spectra is that the electrons are trapped on closed magnetic lines of force in a region where there exists a transverse electric field. The particle drift due to the combined electric and magnetic forces is such as to drive the electron across electric equipotentials producing the energization. This sort of model has been discussed by Axford and Hines (1961) in a qualitative fashion and quantitatively by Taylor and Hones (1965).

The second distinctive feature of these low energy electron influxes is the stability of the characteristic energy in the beam over relatively long periods of tine (> 280 sec). This suggests that source or generator of the required electric potentials can be considered a "d.c." generator - at least until the auroral breakup phase. This in turn suggests that it is this generator which is the mechanism which provides the energization of the electrons involved in the static or pre-breakup phase of the auroral display. The observation of electron energy spectra with peaks during the breakup or dynamic phase of the display may simply mean that electrons, initially trapped, are being discharged into the atmosphere at this time still possessing the characteristic energy acquired during the static phase preceeding breakup.

A final point of some importance is the lack, thus far, of observations of characteristic energies above 15 keV. This coupled with the estimates of about 50 kV (Taylor and Hones, 1965) as the maximum available potential difference in the magnetosphere requires that a second acceleration mechanism be operating to produce those electrons of energies about 100 keV observed in association with the aurora.

The Dynamic Phase

Typically the auroral display passes from the quiet phase described earlier to the breakup phase at some time near local midnight. The breakup phase is characterized by very rapidly moving forms and very extensive, bright aurora. This portion of the display may develop and pass through its peak within a period of 10 minutes or so.

Because it is this phase of the display which is the most intense, many if not most sounding rockets are fired at this time. The observations of electrons (usually greater than 40 keV) on such flights very often are characterized by rapid intensity and spectral fluctuations (Maehlum, 1967). This appears to be especially true of those electrons above 40 keV which often exhibit orders of magnitude fluctuations while the lower energy electron influx remains more or less constant (Evans, 1966). The rocket and satellite experimental study of the > 40 keV component of the auroral particle influx has lead to some general conclusions about their origin. O'Brien (1964) states ".... and becuase the precipitated particles (electrons > 40 keV) must have been generated very recently and could not have been trapped with the same energy and the same pitch angle, we will call each increment of flux at each pitch angle "fresh" particles" thereby implying processes affecting electron within the time of one bounce period or so. Mozer (1966) comes to much the same conclusion and states explicitly "auroral electrons of all observed energies (> 65 keV) and pitch angles probably underwent significant changes of energies and/or pitch angles on each bounce owing to nonatmospheric interaction mechanisms." Mozer's rocket borne observations were made in a breakup aurora.

Evans (1967a) has reported the observation of rapid, periodic energetic electron intensity fluctuations which were interpeted as being caused directly by the mechanism which was energizing these electrons. Figure 5 displays an example of this periodicity. Evans argued on grounds of plausibility that these fluctuations were purely temporal in nature rather than caused by the relative motion of the rocket and a spacially periodic electron influx. A cross correlation analysis was then applied to the electron intensity fluctuations as observed at various energies so as to expose any velocity dispersion effects. The result was that from electron energies of 16 keV to 120 keV there was no observable dispersive effects while there was evidence that fluctuations in 8 keV electrons actually <u>lead</u> in time similar fluctuations at higher energy. This lead to the conclusion that whatever the cause of the modulation, it lay within a distance of some 1000 km of the rocket. Models in which a dumping mechanism modulated a pre-existing beam of electrons and in which the 10 cps periodicity shown in Figure 5 was fundamental to the process which created the electrons involved, were both considered. Because the periodicity was strongest in the higher energy electrons and virtually non-existant in the lowest energies measured, it was concluded that a dumping modulation mechanism would be very special in that it affected only high energy electrons. This was regarded as unlikely and the second explanation - i.e. there was a dynamic energization mechanism at work having a basic 10 cps oscillation - was accepted.

Much evidence has been put forth recently - mostly on the basis of careful study of transistory fluctuations in electron intensity - that some process, modulation or acceleration, is affecting electrons close to the ionosphere (Mozer 1967, Lampton 1967, Winiecki 1967). Fritz (1967) presents further evidence from satellite data that argues for the acceleration of electrons at low altitude over the auroral zone. The sole direct evidence thus far for modulation of auroral electrons at large distances from the earth is presented by Bryant el al (1967) who, on the basis of velocity dispersion arguments, place the modulation region at the equatorial plane.

The observation of these 10 cps periodicities by Evans occurred on the same flight and at the same time that the characteristic peaked spectrum shown in Figure 2 was observed. The appearance of the 6 keV monoenergetic component in the low energy spectrum together with the . dynamic production of 60 keV electron was reminiscent of the laboratory plasma experiments of Smullin and Getty (1962), that in which the introduction of a beam of fast (~ keV) electrons into a plasma resulted in the rapid generation of very energetic electrons. In analog with the processes thought to exist in the laboratory interaction, the following sequence of events was proposed to explain the observations in the breakup aurora.

The 6 keV beam of electrons, which was produced by drift of electrons through a static potential distribution. as described above, interacted with the upper ionospheric plasma to produce plasma instabilities and associated waves. The energy for the waves comes from the particle beam. If the energy given up by the 6 keV electrons is primarily from the $E_{perp.}$ component, the growth of the instability will be accompanied by the dumping of these keV energy electrons. The wave may then interact in a resonant fashion back upon some favored electrons to accelerate them to the observed 60 keV energies. This whole process oscillated at ~ 10 cps to produce the observed periodicity.

This sequence of events has some very satisfying features about it.

(1) It takes the energy represented by the population of 6 keV electrons, energized by something akin to the Taylor-Hones model and trapped on the auroral zone line of force, and suddenly dissipates some portion into the atmosphere explaining the typical flash brightening of the aurora at breakup.

(2) Simultaneously some of this energy is utilized to accelerate electrons to very high (> 50 keV) energies. This would explain why the > 40 keV electron population seems so well associated with the breakup auroral forms (Maehlum, 1967).

(3) Instability processes originating at relatively low altitude would seem to have the best chance of generating the fine spacial and temporal structure seen in the breakup aurora without such features

being "washed out" as would be the case if large transit distances were involved.

Certain features of this picture of course remain to be explained. For example:

(1) Why should the instability suddenly appear in an arc or form hitherto stable (some property of the ionosphere? or of the electron energy?).

(2) What exactly is the nature of the instability and the associated waves. The fact that the conclusions of Evans would indicate that the electrons involved in the periodicity acquired their 100 keV of energy in a time of about 10 msec may have some bearing on this.

However, the dynamic production of energetic (> 40 keV) electrons - probably at low altitude - seems now to be fairly well established.

Summary

This paper has attempted to sketch a possible sequence of events - as seen from the point of view of an electron - from the quiet, prebreakup phase of the aurora through the breakup phase.

It is argued that the pre-breakup aurora is produced by electrons energized by drift through a static magnetospheric potential distribution where the electric field is imposed perpendicular to the geomagnetic line of force. Characteristic peaks and knees in the electron energy spectrum bear testimony to this. It is suggested that the maximum electron energy produced in this manner is about 15 keV.

Due to some, as yet unknown reason, the interaction of this beam of electrons with its plasma environment produced a gross plasma instability. It is surmised that this process takes place at low altitude (~ 1000 km) at times, if not exclusively. The energy feeding the instability comes from the population of low energy (< 15 keV) trapped on that particular line of force, the particle's total kinetic energy acting in a sense as a fly wheel. The onset of this instability may have three relavent aspects insofar as visual auroral morphology is concerned, First if the instability is fed primarily at the expense of the perpendicular component of the trapped electron's energy, dumping of these lower energy electrons occurs which could be the origin of the flash brightening at breakup. Secondly the plasma waves generated in this instability are proposed as coupling back upon favored electrons to accelerate these to high energy (higher than magnetospheric potential differences could account for). Thirdly the association of an instability with the breakup phase of auroral display is, in itself, intuitively satisfying for anyone who has observed this spectacular and very dynamic phenomena.

References

Albert, R. D. "Nearly monoenergetic electron fluxes detected during a visible aurora", Phys. Rev. Letters, 18, pa 369-372, 1967.

Axford, W.I. and L. O. Hines, "A unifying theory of high-latitude geophysical phenomena and geomagnetic storms", Can. J. Phys., 39, pa 1433-1464, 1961.

Bryant, D. A., H. L. Collin, G. M. Courtier, and A. D. Johnstone, "Evidence for velocity dispersion in auroral electrons", Nature, 215, pa 45-46, 1967.

Evans D. S. "Rocket observations of low energy auroral electrons", Aurora and Airglow, pa 191-209, Reinhold Publishing Corporation, 1967. (Paper delivered at Keele, England Aug. 1966).

Evans, D. S. "A 10 cps periodicity in the precipitation of auroral - zone electrons" J. Geophy. Res., 72, 4281-4292, 1967a.

Evans, D. S. "The observation of a near monoenergetic flux of auroral electrons" submitted to the J. Geophys. Res. 1967b.

Fritz, T. A, "Spectral, spacial, and temporal variations observed for outer zone electrons from 10 to 100 keV with satellite Injun 3", Ph.D thesis, Univ. of Iowa 67-42, August 1967.

Lampton, M. "Rapid time structure in daytime electrons", paper delivered at the 48th Annual Meeting of the American Geophysical Union, April 17-20, 1967, Washington D. C.

Lampton, M., R. Albert, K. A, Anderson, and L. M. Chase " Rocket observations of charged particles in the auroral zone" paper delivered at the Birkeland Symposium, Sandefjord, Norway, Sept. 18-22, 1967.

Maehlum, B., "Satellite and rocket measurements in the auroral zone", paper delivered at the Birkeland Symposium, Sandefjord, Norway, Sept. 18-22, 1967.

Mende, S. B. "Upper limit for electric fields parallel to the magnetic field in the auroral ionosphere", Department of Space Science, Rice University, 1967.

Mozer, F. S. "Rapid variation of auroral particle fluxes", Univ. of California, Space Science Laboratory, July, 1967.

Mozer, F. S. and P. Bruston, "Properties of the auroral zone electron source deduced from electron spectrums and angular distributions", J. Geophy. Res., 71, 4451-4460, 1966.

O'Brien B. J., "High-latitude geophysical studies with Injun 3. 3. precipitation of electrons into the atmosphere", J. Geophys., Res., 69, 13-43, 1964.

Smullin, L. D. and W. D. Getty, "Generation of a hot, dense plasma by a collective beam plasma interaction", Phys. Rev. Letters, 9, 3, 1962.

Taylor, H. E. and E. W. Hones, Jr., "Adiabatic motion of auroral particles in a model of the electric and magnetic fields surrounding the earth", J. Geophys. Res., 70, 3605-3628, 1965.

Winiecki, T., "Analysis of rapid temporal fluctuations in auroral particle fluxes", M. Sc. Thesis, Space Science Department, Rice University, Houston, Texas, 1967.

Figure Captions

Figure 1 Sample electron differential energy spectra observed on flight 14.188 (Evans, 1966)

Figure 2 Sample electron differential energy spectra observed on flight 14.189 (Evans, 1966).

Figure 3 A sample of the swept energy detector response observed on flight 18.24. The scatter in data has been reduced by a running average technique. The solid line is that response that would have been expected had the electron beam been purely 3.8 keV electrons. The close agreement between the observed and hypothetical curves lead to the conclusion that the slope of the true energy spectrum above 3.8 keV was less than 100 eV.

Figure 4 The energy of the peak in the electron energy spectra observed on flight 18.24 as a function of time while the rocket was above the auroral display.

Figure 5 A high time resolution count rate plot of several detectors during a time of periodic fluctuations observed on flight 14.189.

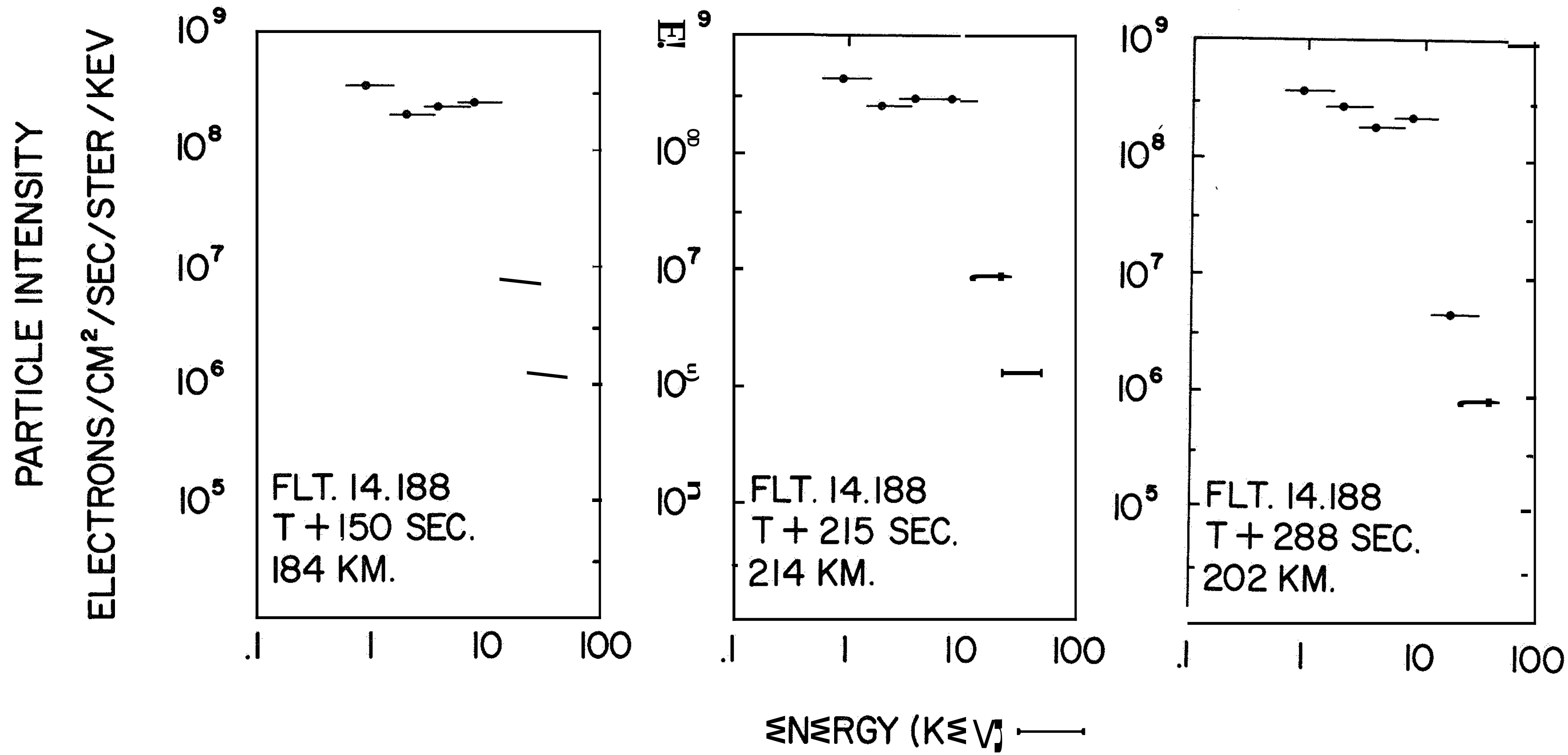

PARTICLE INTENSITY
ELECTRONS/CM²/SEC/STER/KEV
10⁹
10⁸
10⁷
10⁶
10⁵
FLT. 14.188
T + 150 SEC.
184 KM.
FLT. 14.188
T + 215 SEC.
214 KM.
FLT. 14.188
T + 288 SEC.
202 KM.
.1
1
10
100
ENERGY (KEV)

FIGURE 1

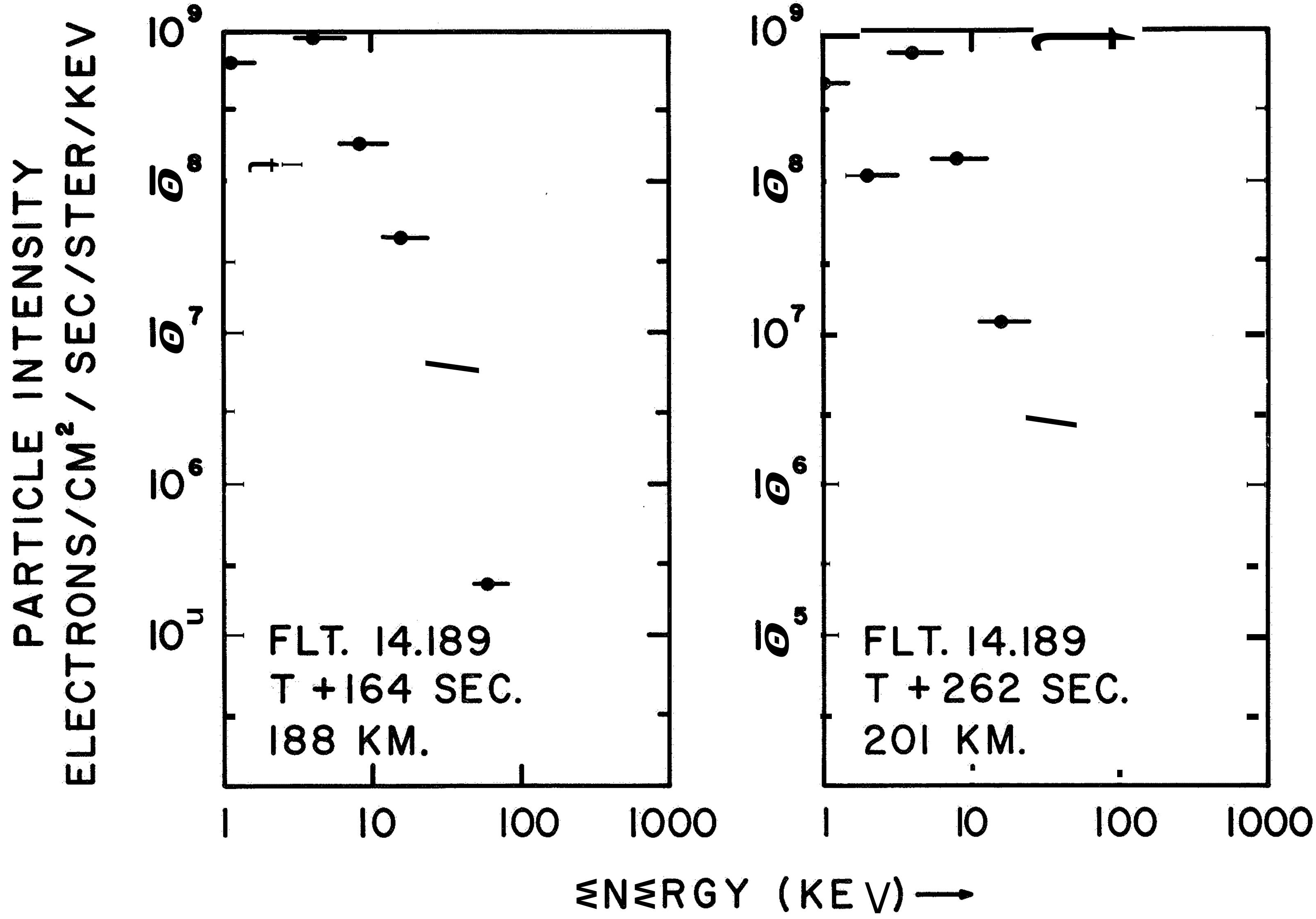
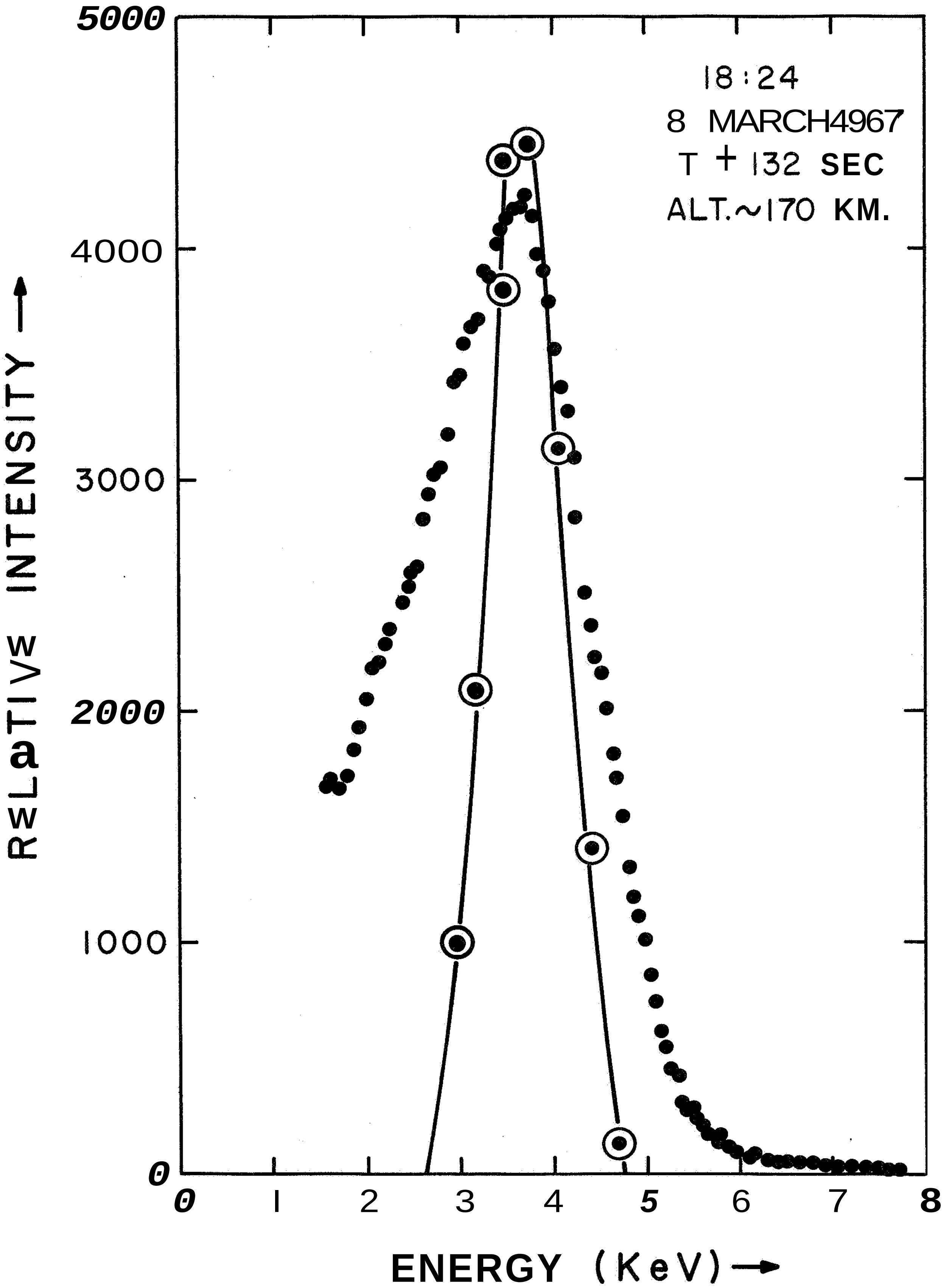

PARTICLE INTENSITY
ELECTRONS/CM²/SEC/STER/KEV
FLT. 14.189
T +164 SEC.
188 KM.
FLT. 14.189
T + 262 SEC.
201 KM.
ENERGY (KEV)

FIGURE 2



18:24
8 MARCH4967
T + 132 SEC
ALT.~170 KM.
5000
4000
3000
2000
1000
0
RWLaTIVW INTENSITY
0
1
2
3
4
5
6
7
8
ENERGY (KeV)

FIGURE 3

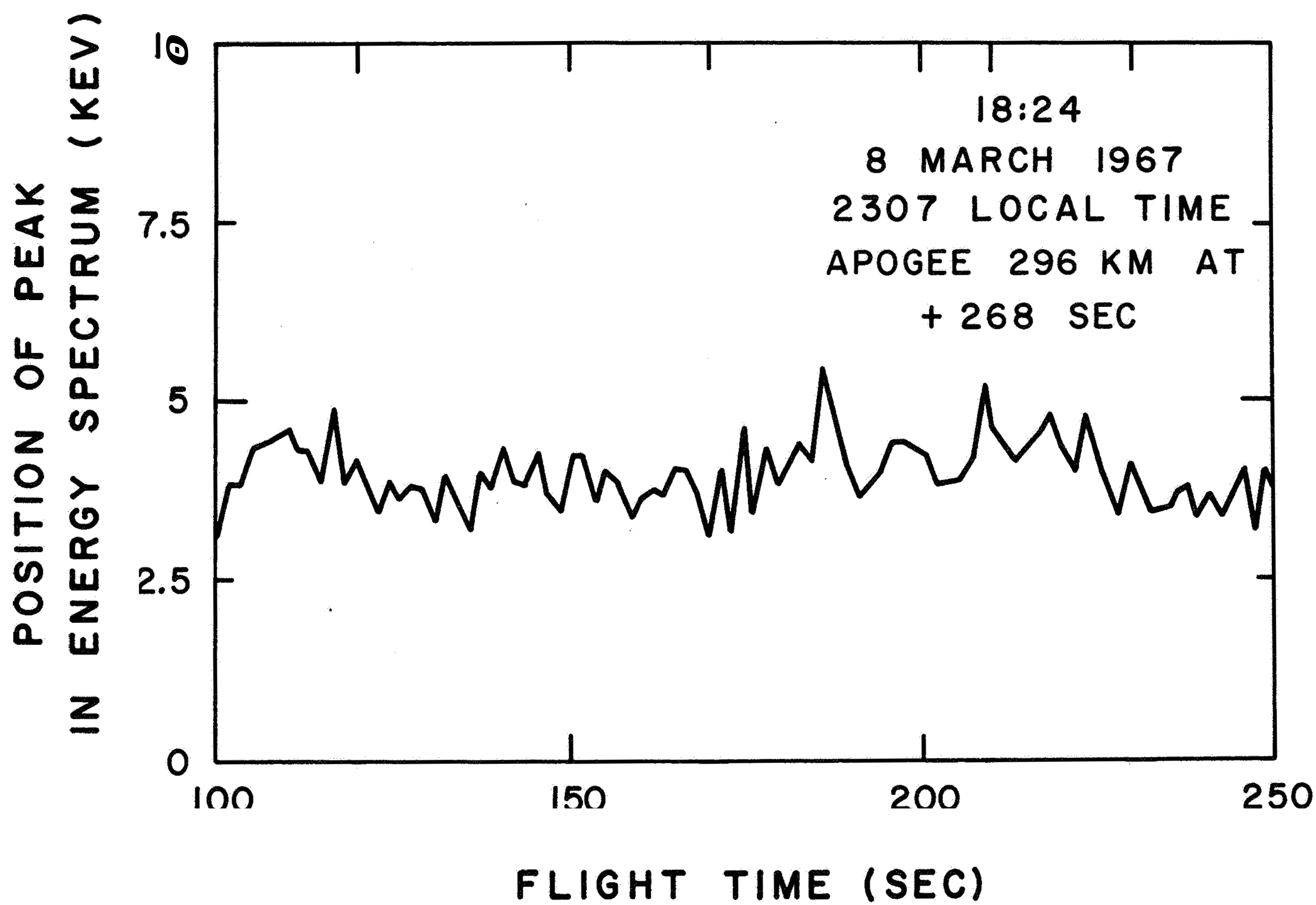
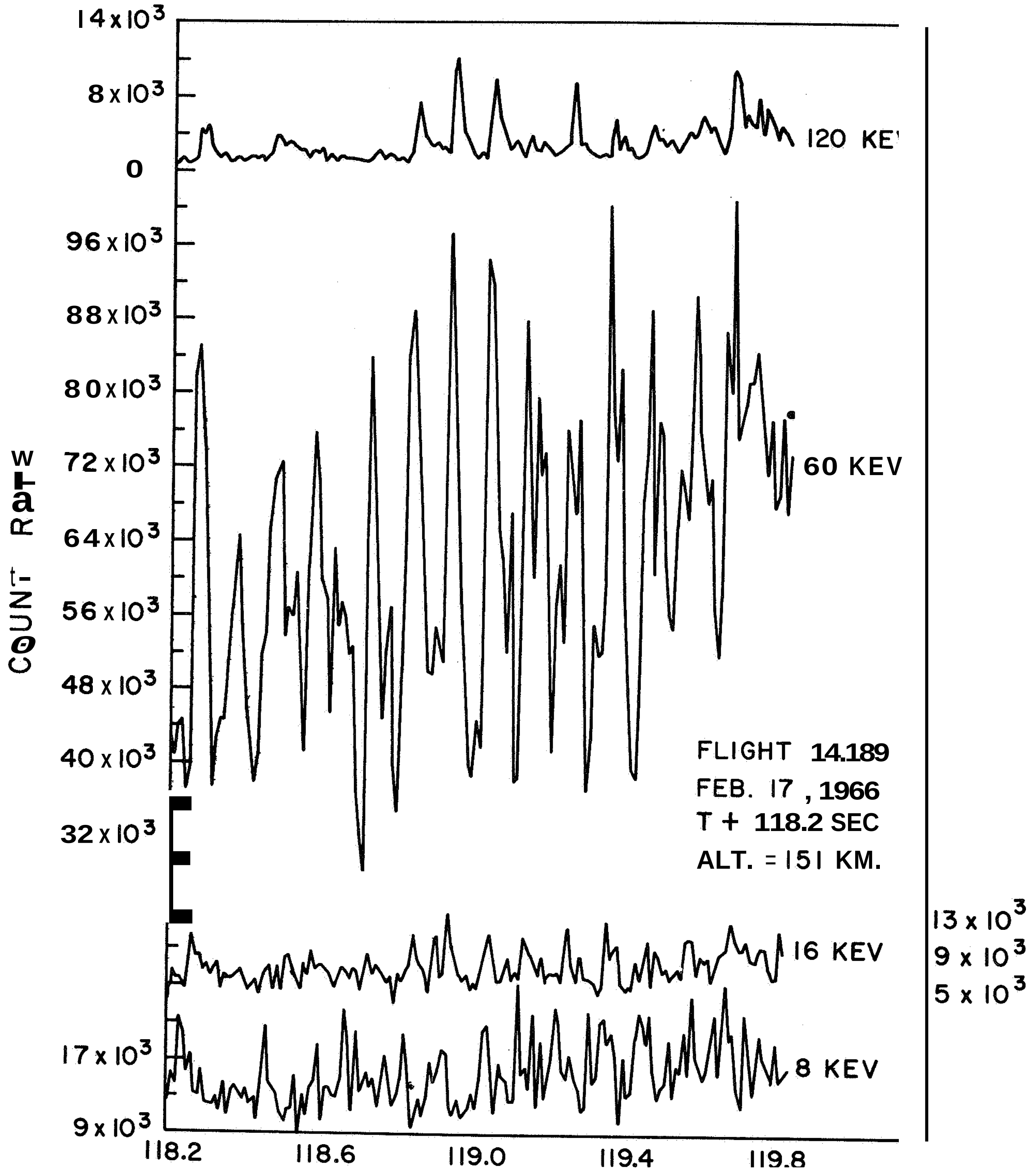

18:24
8 MARCH 1967
2307 LOCAL TIME
APOGEE 296 KM AT
+ 268 SEC
POSITION OF PEAK
IN ENERGY SPECTRUM (KEV)
10
7.5
5
2.5
0
100
150
200
250
FLIGHT TIME (SEC)

FIGURE 4



14 x 10^3
8 x 10^3
0
120 KEV
96 x 10^3
88 x 10^3
80 x 10^3
72 x 10^3
64 x 10^3
56 x 10^3
48 x 10^3
40 x 10^3
32 x 10^3
60 KEV
COUNT RATE
FLIGHT 14.189
FEB. 17, 1966
T + 118.2 SEC
ALT. = 151 KM.
13 x 10^3
9 x 10^3
5 x 10^3
16 KEV
17 x 10^3
9 x 10^3
8 KEV
118.2
118.6
119.0
119.4
119.8
TIME

FIGURE 5